Impact of Z-Direction Fiber Orientation on Performance of Commercial and Laboratory Linerboards

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The Opportunity

Cellulose fibers tilted out-of-plane can bond with multiple strata, potentially improving the compression strength of paper.

Fibers generally occupy layers parallel to the plane of the sheet. However, some fibers tilt out-of-plane owing to drainage forces on the wire. A tilt angle as small as 5° allows a fiber segment of 200-micron length to bond with fibers in 3 or 4 distinct layers. This makes it harder for layers to slide across each other when they experience shear forces. Improved out-of-plane shear should lead to better compression strength as well [1].

Hydrodynamic forces in the forming process provide a mechanism for generating fiber tilt. They are likely to cause one end of an MD-oriented fiber to migrate downward toward the wire side.

As shown in Figure 1, paper made under drag conditions is likely to have fibers with ends closest to the reel lying closer to the wire side [2]. Tilt is reversed for papers made under rush conditions.

Re-orienting fibers to have more tilt can be a way to increase performance with low added capital cost.

There aren't too many tilted fibers in most sheets. Figure 2 shows two in one micrograph but this is not typical. Re-orientation of relatively few fibers from in-plane to out-of-plane could have important effects. It could help to accomplish strength and stiffness improvements using small process adjustments at low capital cost.

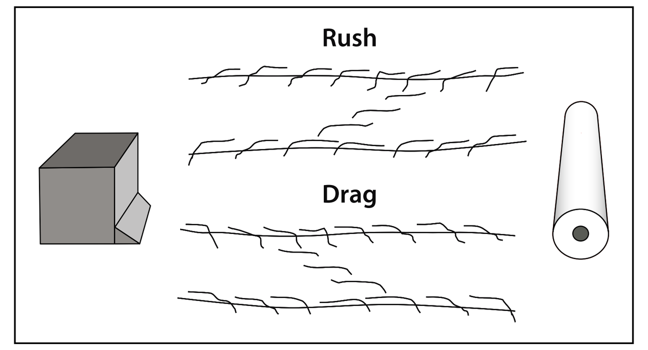

Figure 1. In MacGregor's hydrodynamic model [2], fibers can tilt up or down depending on rush or drag on the Fourdrinier. We refer to this as ZDFO.

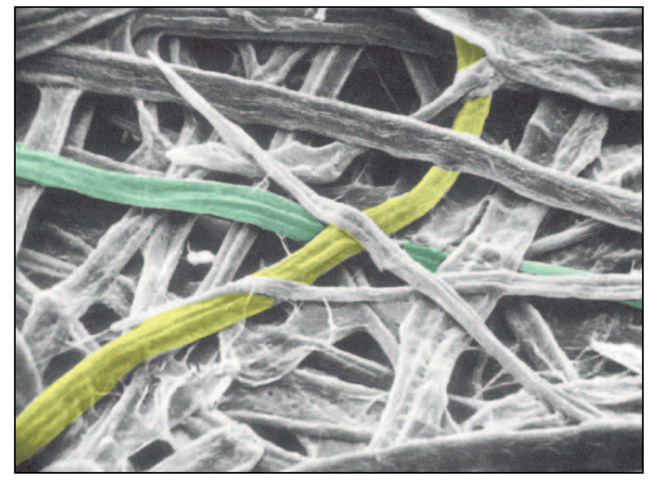

Figure 2. Z-direction fiber orientation (ZDFO), also known as fiber tilt. Several highlighted fibers in this image appear to cross multiple strata. From Forest Products Laboratory archives.

The Measurement

Unfortunately, the old adage, "If you can measure it, the papermaker can improve it" has not had a chance to work when "it" refers to fiber tilt. The concentration and angle distribution of tilted fibers in paper can't yet be directly measured.

Indirect measurements related to tilted fibers have been mostly restricted to surface tape pulls [2]. Imagine a tape applied to the paper surface represented in Figure 2. Pulling the tape from left to right catches the free end of the two highlighted fibers and uproots fibers in the strata that they penetrate. These same strata would shield the fibers if the tape were pulled from right to left. The model of Figure 1 can be expanded to show that fibers oriented in the CD can acquire tilt when exposed to cross-machine flows. Significant disruption has been observed for tape pulls along both the machine direction (MD) and cross-machine direction (CD).

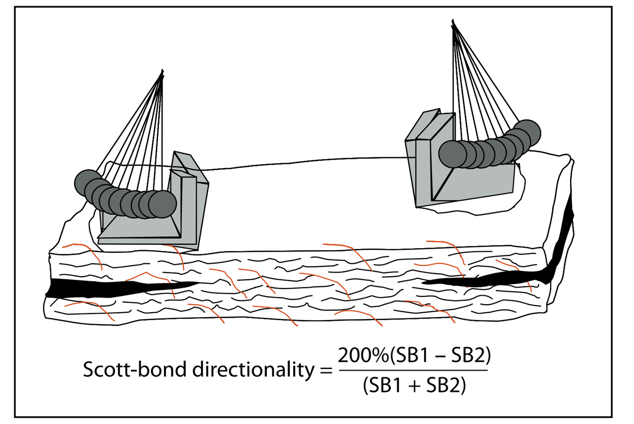

Figure 3. Scott-bond testing in two opposing directions can provide an indirect measurement of ZDFO, expressed as a percentage of the measurement differential. SB1 and SB2 are average Scott-bond values for 50 tests in each direction.

For heavier grades, we looked for signs of ZDFO by measuring Scott-bond test differences in opposing directions [3]. The percentage change in value with direction is an indirect measurement of z-direction fiber orientation (ZDFO). The experiment shown schematically in Figure 3 assumes that tilted fibers (shown in red) will offer different resistance to Scott-bond stresses according to the testing direction. The percentage difference in Scott-bond value with direction becomes an indirect measurement of ZDFO when the tilted fibers have a preferred slope, as in the hydrodynamic model of Figure 1.

The experiment will not be sensitive to cases where the distribution of slopes of tilted fibers averages to zero. Such papers can have high plybond or Scott bond without displaying directional sensitivity. Our directional measurement of ZDFO does not at present include these fibers.

Commercial Linerboards

The Tests

Table 1 shows the Scott-bond differential and other physical properties for three tested linerboards, designated as either A, E or F. By coincidence, the three liners showed distinctly different characteristics of ZDFO: F had ZDFO in the MD only. E had no ZDFO, and A had ZDFO in the CD.

The symbol ~0 indicates values that were not statistically different than 0 at the 95% confidence level. Scott-bond test values averaged over both directions are also shown in Table 1. Sample E had the largest value. It may have had ZDFO of a type not measured by directional testing; alternatively, it may simply have had better ply-to-ply bonding without any ZDFO.

Table 1. Physical properties and Scott-bond directional differences as a percentage of average Scott-bond value for three linerboards.

	Linerboard		
	A	E	F
Grammage (g/m²)	268	209	214
Caliper (mm)	0.41	0.30	0.33
Density (kg/m³)	660	688	645
MD Scott-bond directionality (%)	~0	~0	2.9
CD Scott-bond directionality (%)	2.9	~0	~0
MD Scott bond (J/m²)	168	196	168
CD Scott bond (J/m²)	174	199	169

Table 2 shows the results of strength and stiffness testing. The results were normalized by dividing by basis weight (or by density, in the case of Taber stiffness). Values for linerboard F tend to be the largest and values for A the smallest. All values were further normalized to a percentage scale and plotted in Figure 4 for easy comparison. The various tests performed are ordered along the x-axes of Figure 4, roughly in order of increasing sensitivity to ZDFO.

Tensile tests of stiffness and strength are expected to be insensitive to ZDFO. Short-span compression strength [4] and Taber bending stiffness [5] are more sensitive, and the double-notch-shear (DNS) test [6] described in the appendix is likely to be most sensitive to ZDFO. The error bars in Figure 4 represent one standard error.

Table 2. MD and CD physical properties of Linerboards A, E and F. Highlighted cells indicate the largest MD and CD values for a given test.

	Linerboard–Direction					
Property	A–MD	E–MD	F–MD	A–CD	E–CD	F–CD
Scott-bond directional differential (ZDFO, %)	~0	~0	2.9	2.9	~0	~0
Tensile strength index (N·m/g)	53.6	68.5	66.3	26.4	33.8	30.8
Ultrasonic tensile stiffness index (kN·m/g)	11.9	12.3	14.7	5.4	5.9	6.0
Tensile stiffness index (kN·m/g)	3.99	4.58	4.84	3.02	2.95	3.25
Compression strength index (N·m/g)	29.8	33.7	33.8	18.7	19.9	20.1
Taber stiffness index (kN·m/g)	5.81	7.33	7.56	2.57	3.04	2.97
Out-of-plane shear index (DNS, N·m/g)	9.11	8.32	11.83	5.23	5.28	5.49

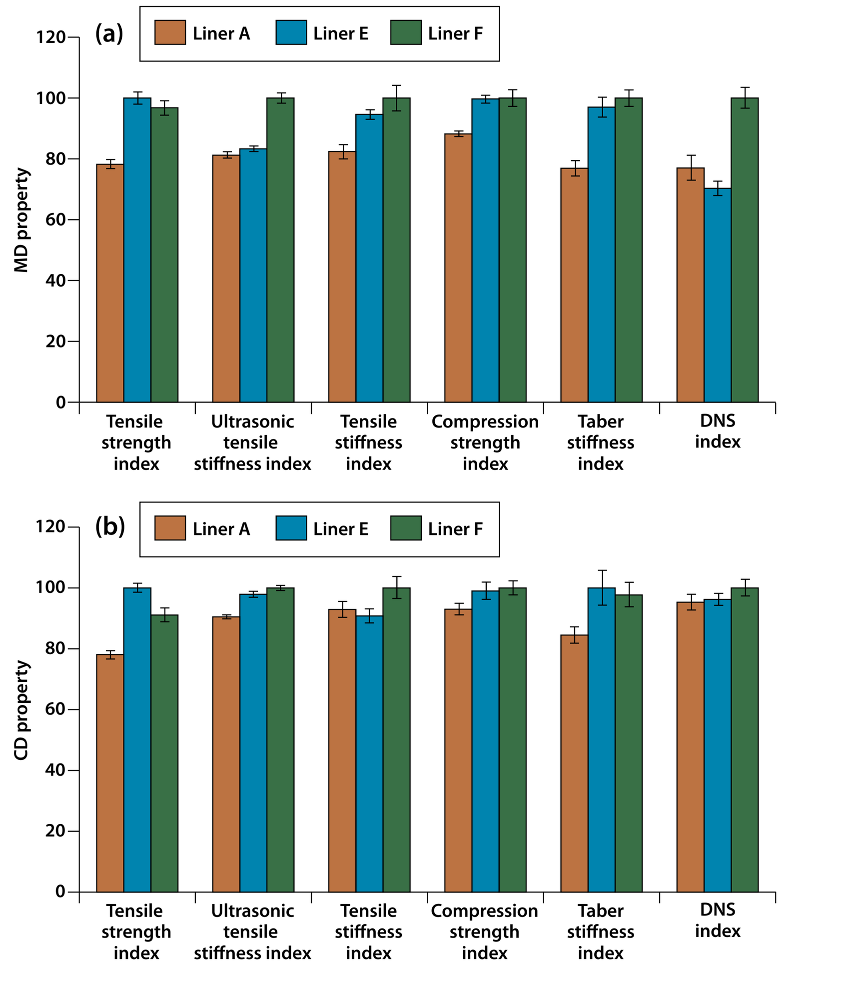

Figure 4. Relative values of strength and stiffness for linerboards A, E and F. (a) MD and (b) CD.

Among MD strength and stiffness tests of samples A, E and F, double-notch shear (DNS) strength of sample F was significantly larger than for either A or E. This strength advantage was missing in CD testing. It is easiest to associate this result with the finding of ZDFO in the MD of F but not in the CD of F, and not in E.

In compression and bending stiffness tests, F and E performed comparably. Recall from Table 1 that E had the largest average Scott-bond value. The implied large plybond may have helped E to match the performance of F in tests other than DNS.

Perhaps a better comparison is between F and A, since both had comparable Scott-bond values but different ZDFO. Sample F is superior to A in all MD and CD tests; however, the relative performance of A is greatly improved in all of the CD tests. This is consistent with the observation of CD-ZDFO in sample A and the absence of CD-ZDFO in sample F. Sample A also improves relative to sample E in most CD tests.

Among CD strength and stiffness tests of samples A, E and F, the relative improvement of sample A relative to E and F reinforces a possible correlation with ZDFO.

Conclusions—Linerboard Tests

As interpreted, the results suggest an association between ZDFO and out-of-plane shear performance of three linerboards. The results are encouraging but not definitive. Scott-bond differential testing is indirect and limited to ZDFO having a preferred slope or tilt angle. The linerboards tested were similar but not of the same origin or grade. Other interpretations of results, such as those based on relative squareness of the sheets, remain to be examined.

➡ Better-controlled samples are needed to show the benefits of ZDFO without the uncertainties caused by competing variables in commercial papers…

➡ Handsheets Using Synthetic Fibers to Create ZDFO

Materials

We made modified TAPPI handsheets from eucalyptus fibers. In addition to control sheets made from only eucalyptus, experimental sheets incorporated 10% synthetic fibers by weight. The synthetic fibers were either stiff carbon fibers or flexible rayon fibers.

The handsheets averaged 215 g/m² and 0.41 mm caliper. The eucalyptus freeness was 630 ml CSF and the mean weighted fiber length was 0.57 mm. Rayon fibers were nominally 15 µm in diameter, 3 mm long, and had density in the range 1480 to 1540 kg/m³. Straight, stiff carbon fibers were nominally 7 µm in diameter, 3 mm long, and had a density of 1800 kg/m³. Neither rayon nor carbon fibers bonded to the eucalyptus fibers. Rayon fibers had low bending stiffness and were easily intertwined with the eucalyptus fibers. They were used to show the effect of non-bonding, flexible fibers in the fiber network, in contrast with the effect of non-bonding, stiff carbon fibers.

Modifications of a standard handsheet former [7,8] were intended to increase the probability for synthetic fibers to land vertically on the forming screen and fiber mat and then fall over one another creating an open 3-D network that could be filled by tilted cellulose fibers; that is, ZDFO. It was expected that carbon fibers, being much stiffer than rayon, would better accomplish this.

Testing

Handsheets were subjected to tensile strength and double-notch-shear testing, with the results shown in Figure 5.

Rayon fiber merges with the cellulose fiber network without bonding. The loss of bonding sites results in 18% loss of tensile strength and 16% loss of DNS strength. In the case of carbon fiber, bonding sites are assumed to be lost as well. However, the tensile strength loss is less than 1% and the DNS strength actually experiences a gain of 14%. We attribute this to the formation of eucalyptus fiber ZDFO in the vicinity of the carbon fibers.

The number of tests was 19 tensile and 69 DNS, with slightly less than half the testing done on control samples. The error bars in Figure 5 represent ± two standard-errors deviation from the average value.

Figure 6 is an optical micrograph showing a several dark carbon fibers in a cross-section of handsheet. Cellulose fibers encountering this structure acquire ZDFO and ultimately bond with each other and with stratified fibers to give the observed strength effects.

At 3 mm length and too stiff to bend under the hydraulic forces of handsheet manufacture, carbon fibers are unlikely to stratify. The tilt angle of 7° is consistent with the fiber's length and the handsheet caliper of 0.4 mm. Some evidence of z-oriented eucalyptus fibers is seen in Figure 6, though this could also represent disruption caused in preparing the specimen.

Figure 7 is a synchrotron x-ray microtomograph showing an interior section of a eucalyptus-carbon-fiber handsheet [9]. Several straight fiber segments, presumed to be carbon, are seen oriented diagonally within the image. One in the upper right of the image appears to dive into the surface. A circular arc of disruption, not expected in a paper structure, appears to be associated with this event. The scale of the disruption is about 0.35 mm diameter, comparable to the weighted-average eucalyptus fiber length of 0.57 mm.

Figure 8 shows contrast enhanced synchrotron x-ray radiographs taken through the cross-section of eucalyptus handsheets containing carbon and rayon fibers. Vertical projections of carbon fibers are common. Since the fibers are 3 mm long, these are projections of fibers that generally extend into or out of the plane of the image. In Figure 8b rayon fibers are seen to blend more with the general cellulose structure.

In the lots from which the imaged samples were taken, the average density of carbon-fiber handsheets was 480 kg/m³. For sheets with rayon, the density was 530 kg/m³. For the control handsheets, the density was 560 kg/m³. Carbon fiber had 2.7 times the effect on density that rayon fiber had, indicating the greater degree of disruption to the cellulose structure.

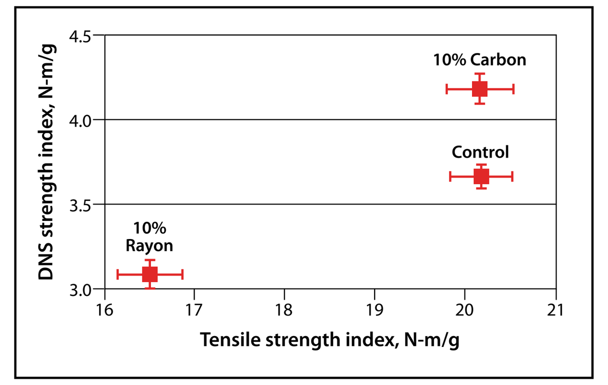

Figure 5. Results of DNS and tensile strength testing of handsheets with and without synthetic fibers.

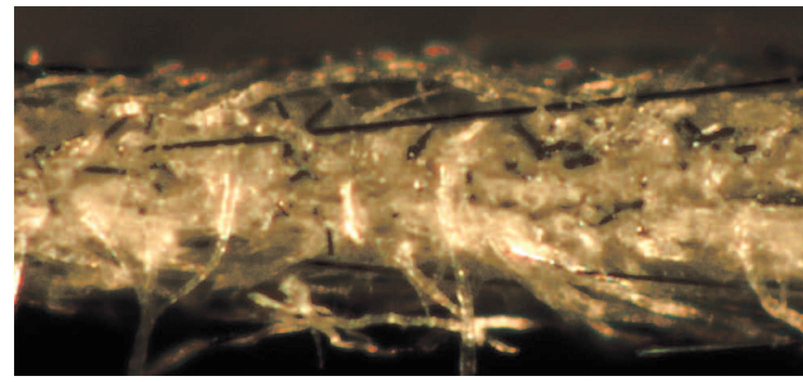

Figure 6. Cross-sectional view of a eucalyptus handsheet containing 10% carbon fibers by weight.

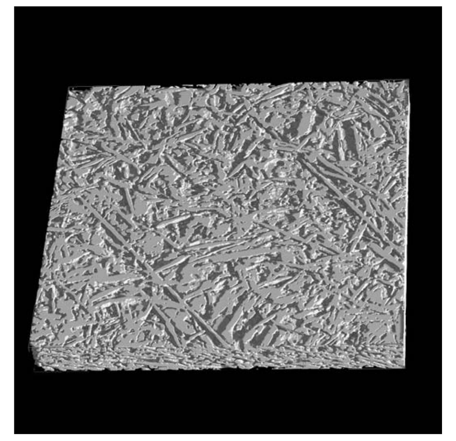

Figure 7. An interior section from a eucalyptus/carbon-fiber handsheet obtained using synchrotron x-ray microtomography. Dimensions are 700 * 700 * 70 µm³.

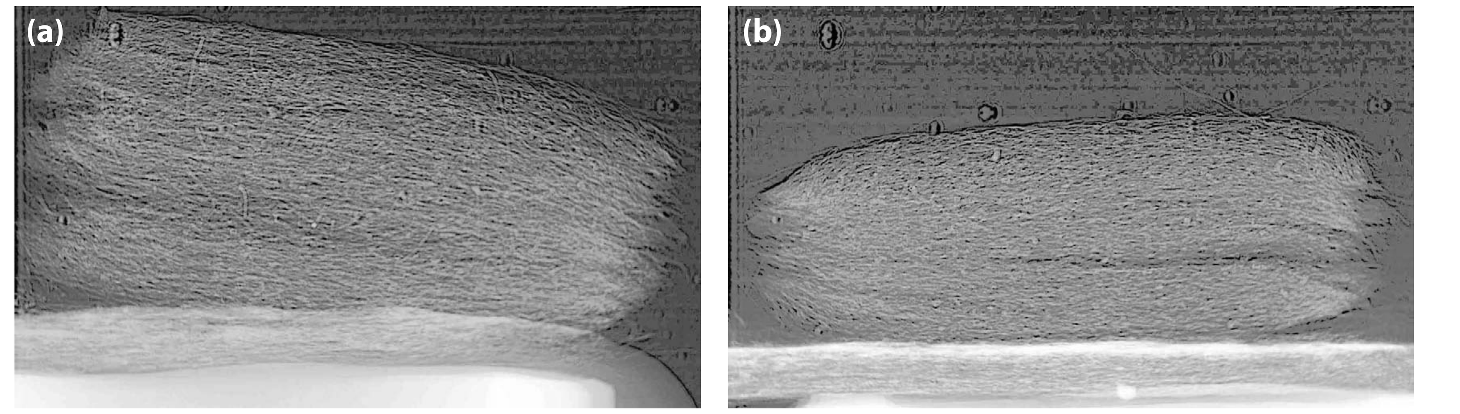

Figure 8. X-ray radiographs of eucalyptus handsheets containing 10% carbon fiber (a) or rayon fiber (b). The scale of the images is 1400 µm horizontal by 840 µm vertical.

Conclusions—Handsheet Studies

X-ray images show that carbon fibers do not stratify in handsheets. Logic suggests that eucalyptus fibers acquire ZDFO as they encounter these stiff structures just before they encounter the fiber mat. Testing shows that the network so generated is able to overcome the 10% sacrifice of weight to non-bonding material. Tensile strength is maintained and out-of-plane shear strength as measured by the DNS test is increased 14%. Parallel experiments with rayon fiber show the expected loss of strength and make the arguments more convincing.

These experiments are not meant to promote the use of synthetic fibers in commercial papermaking, especially carbon fibers. They are meant to suggest the strength and stiffness improvements that can result from papers with ZDFO, however obtained. Some forms of natural fibers suited for papermaking, such as stiff recycled fibers (from hornification) and fibers with three-dimensional structure (from certain pulping operations) are worth investigating.

Appendix: The Double-Notch-Shear Test

The double notch shear (DNS) test is a simple method for determining out-of-plane shear strength [6]. A tensile test is performed using the sample shown in Figure 9. A requirement for success is that shear failure occurs in the span between the two notches. The span used for testing linerboard samples was 1.59 mm (1/16 inch) and the span used for testing eucalyptus handsheets was 2 mm. Larger spans are possible using laminated specimens [10].

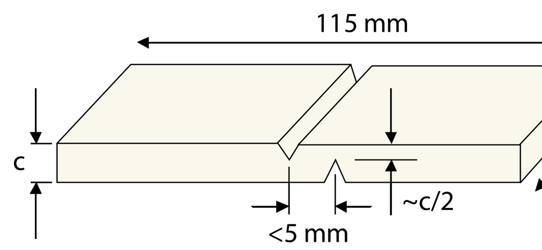

Figure 9. Sample geometry for double-notch-shear (DNS) test for out-of-plane shear strength.

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Abstract

Fibers tilted in z-direction by hydraulic forces associated with rushing or dragging the sheet can bond multiple strata together, resulting in improved out-of-plane shear strengths. Tilted fibers are difficult to identify microscopically; however, their presence can result in different measurements of Scott internal bond when tests are carried out in the two opposing machine directions. These tests identified differing fiber tilts that correlated with differing amounts of out-of-plane shear strengths in three otherwise comparable linerboard samples. The effect was duplicated in handsheets in which stiff, non-bonding carbon fibers were added to pulp to produce three-dimensional structures that interfered with the tendency of draining fibers to stratify. Even though the substitution of 10% carbon fibers produced a loss of bonding sites, the out-of-plane shear strength of the handsheets improved by an average of 15%. The search is on for methods to control fiber tilt in commercial paperboard. Success will result in improved mechanical performance without additional fiber costs.

Introduction

Although paper is a highly stratified material, hydrodynamic forces in the forming process of a Fourdrinier machine are likely to cause one end of a machine-direction- (MD-) oriented fiber to migrate downward toward the wire side. Paper made under drag conditions is likely to have fibers with ends closest to the reel lying closer to the wire side [1]. Tilt is reversed for papers made under rush conditions. Cross-flows associated with fiber misalignment can produce similar tilt effects for cross-machine-direction- (CD-) oriented fibers.

Fibers with segments tilted only a few degrees can intersect multiple fiber layers. By forming bonds within adjacent layers, fibers tie the layers together, potentially increasing ply-bond and out-of-plane shear [2]. These are known to be important components of compression strength [3]. The term z-direction fiber orientation (ZDFO) is used here to indicate the presence of these tilted fiber segments. We believe that ZDFO can play an important role in improving compression strength of structural paperboard without the expense of additional fiber.

The distribution of ZDFO in terms of the concentration of tilted fiber segments and their lengths and angles are important parameters, but no direct measurement is known. Scanning electron micrograph (SEM) images of paper surfaces occasionally show a fiber segment on top of some fibers but below other fibers that appear to be in the same stratum. In our experience, this is difficult to evaluate even in a qualitative way. The principal demonstration for ZDFO has been tape pulls, especially pulls in two opposite directions [1,4,5]. These show greater or less fiber pickup, or peel force, according to the sense of fiber tilt in the pull direction. These tests emphasize fiber tilt at or near the paper surface. There is no guaranty that ZDFO implied by these tests exists throughout the volume of the sheet, as would be appropriate for compression-strength enhancement.

Vahey and Considine [6] conducted Scott internal bond testing [7] on papers in two opposing machine directions (MD+ and MD–) and cross-machine directions (CD+ and CD–) to determine any differential that could be taken as a measure of ZDFO through the volume of a sheet. Roughly ten times the number of replicates normally used for the Scott bond test were required to obtain statistically significant results.

Table 1 shows the Scott-bond differential and other physical properties for three tested linerboards, designated as either A, E, or F. By coincidence, the three liners showed distinctly different characteristics of ZDFO: F had ZDFO in the MD only, E had no ZDFO, and A had ZDFO in the CD.

The symbol ~0 indicates values that were not statistically different than 0 at the 95% confidence level. Scott-bond test values averaged over both directions are also shown in Table 1. Sample E had the largest value. It may have had ZDFO of a type not measured by directional testing; alternatively, it may simply have had better ply-to-ply bonding without any ZDFO.

Samples A, E, and F span a range of ZDFO possibilities that motivated us to perform a battery of conventional strength and stiffness tests on each of them. Along with testing linerboard samples we fabricated and tested handsheets containing 10% carbon or rayon fibers. Because carbon fiber and rayon do not bond with cellulose in paper, strength values should be smaller than in control samples. An opposite observation may suggest that synthetic fibers are conducive to the generation of ZDFO. Handsheets containing synthetic fibers also offer an opportunity for more direct observation of ZDFO using synchrotron image slicing and radiography.

Materials and Tests

Linerboards A, E, and F were discussed in previous publications [2,6,8]. Linerboards A and E are believed to be of commercial manufacture. Although linerboard F has many mechanical properties similar to commercial grade (and generally superior to those of A), it may have come

Table 1. Physical properties and Scott-bond directional differences as a percentage of average Scott-bond value for three linerboards

Linerboard	A	E	F
Grammage (g/m^2)	268	209	214
Caliper (mm)	0.41	0.30	0.33
Density (kg/m^3)	660	688	645
MD Scott-bond directionality (%)	~0	~0	2.9
CD Scott-bond directionality (%)	2.9	~0	~0
MD Scott bond (J/m^2)	168	196	168
CD Scott bond (J/m^2)	174	199	169

from a pilot-scale paper machine. This may have facilitated the significant MD ZDFO observed in the sample and limited cross flows that could produce CD ZDFO.

Three types of handsheets were made:
1. 100% eucalyptus fiber, the control, Brazilian plantation grown, 630 ml CSF
2. 90% eucalyptus fiber, 10% rayon fiber (by weight)
3. 90% eucalyptus fiber, 10% carbon fiber (by weight)

The basic idea was to create a three-dimensional (3-D) structure during handsheet forming to disrupt the tendency of cellulose fibers to stratify, thereby producing ZDFO. A handsheet former modified from TAPPI T 205 [9] was designed to accomplish this. Modifications [8] were intended to increase the probability for synthetic fibers to land vertically on the forming screen and fiber mat and then fall over one another creating an open 3-D network that could be filled in by non-stratified cellulose fibers. We expected that carbon fibers, being much stiffer than rayon, would better accomplish this. The eucalyptus fibers had a weighted average fiber length of only 0.57 mm and were believed more likely than longer fibers to fill in the open network without stratification. Refining of the fibers was limited for the same reason. Handsheet basis weights were 205 g/m^2.

Testing of the handsheets was limited to tensile and double-notch-shear (DNS) [10]. Figure 1 shows a schematic of the DNS strip configuration. The test is conducted like a standard tensile test.

In this work, the span between notches was 2 mm for handsheets and 1.59 mm (1/16 in.) for linerboards, and notches were cut to the approximate middle of specimen caliper. The notches determined a failure surface. Only tests failing in the shear-lap region were considered valid.

The linerboard materials and additional tests performed on them are described in detail in Considine et al. [8]. They include tensile strength and stiffness [11,12], short-span compression strength [13], and Taber stiffness [14]. The important comparisons to be made have to do with relative values: the three linerboards compared with each other and the synthetic-fiber handsheets compared with the control.

Results

Table 2 shows the results of strength and stiffness testing of linerboards. Results were normalized by dividing by basis weight (or by density, in the case of Taber stiffness). Values for

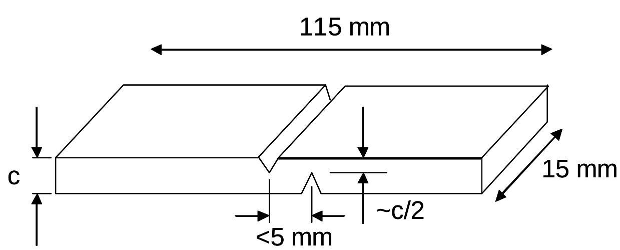


Figure 1. Geometry for the DNS test.

Table 2. MD and CD physical properties of linerboards A, E, and F[a]

Linerboard–Direction	A–MD	E–MD	F–MD	A–CD	E–CD	F–CD
Scott-bond directional differential (ZDFO) (%)	~0	~0	2.9	2.9	~0	~0
Tensile strength index (N·m/g)	53.6	68.5	66.3	26.4	33.8	30.8
Ultrasonic tensile stiffness index (kN-m/g)	11.9	12.3	14.7	5.4	5.9	6.0
Tensile stiffness index (kN·m/g)	3.99	4.58	4.84	3.02	2.95	3.25
Compression strength index (N·m/g)	29.8	33.7	33.8	18.7	19.9	20.1
Taber stiffness index (kN·m/g)	5.81	7.33	7.56	2.57	3.04	2.97
Out-of-plane shear index (DNS) (N·m/g)	9.11	8.32	11.83	5.23	5.28	5.49

[a] Highlighted cells indicate the largest MD and CD values for a given test.

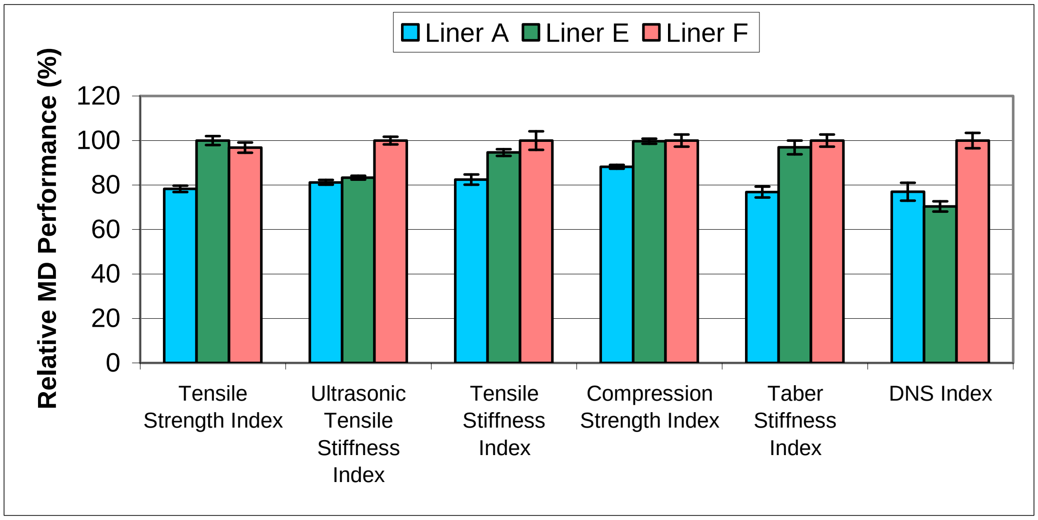
linerboard F tend to be the largest and values for A the smallest. All values were further normalized to a percentage scale and plotted in Figure 2 for easier comparison. The various tests performed are ordered along the *x* axes of Figure 2, roughly in order of increasing sensitivity to ZDFO.

Tensile tests of stiffness and strength are expected to be insensitive to ZDFO. Short-span compression strength and Taber bending stiffness are more sensitive, and the DNS test is likely to be most sensitive to ZDFO. The error bars in Figure 2 represent one standard error.

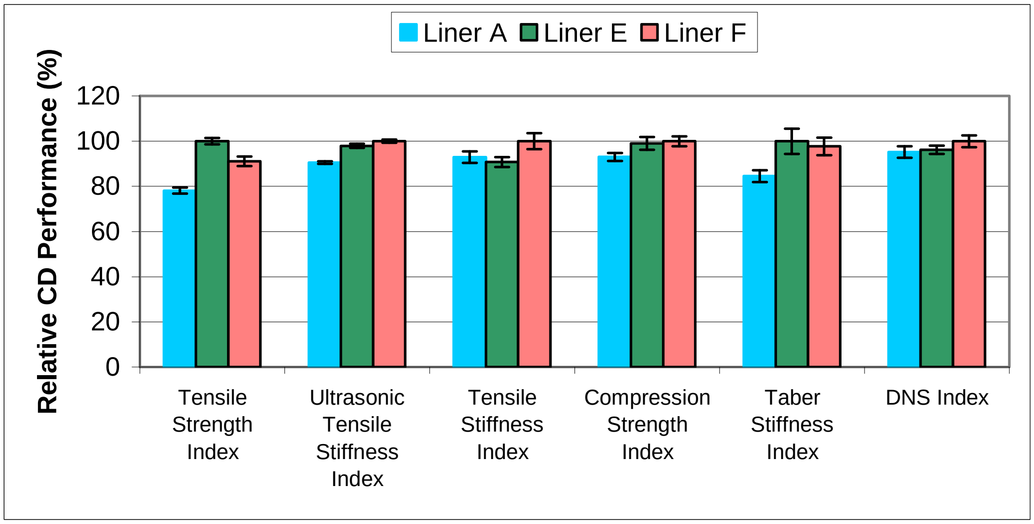
Figure 3 shows results of tensile strength and DNS testing of eucalyptus handsheets. Nineteen tensile tests and 69 DNS tests are represented by the three plotted points, and the error bars represent two standard errors. Neither rayon nor carbon fibers bond with cellulose fibers in paper. Their presence should therefore reduce the strength of handsheets compared with the control. This is the case for handsheets containing rayon fibers with regard to both tensile and DNS testing. The loss of tensile-strength and DNS indices in the handsheets containing rayon is 18% and 16%, respectively. However, it is not the case for handsheets containing carbon fibers, in which the tensile-strength index loss is less than 1% and the DNS gain is 14%.

Analysis and Discussion

Among MD strength and stiffness tests of samples A, E, and F, DNS strength of sample F was significantly larger than for either A or E. This strength advantage was missing in CD testing. It is easiest to associate this result with the finding of ZDFO in the MD of F but not in the CD of F, and not in E.



(a)



(b)

Figure 2. Relative performance of linerboards A, E, and F; (a) MD, (b) CD.

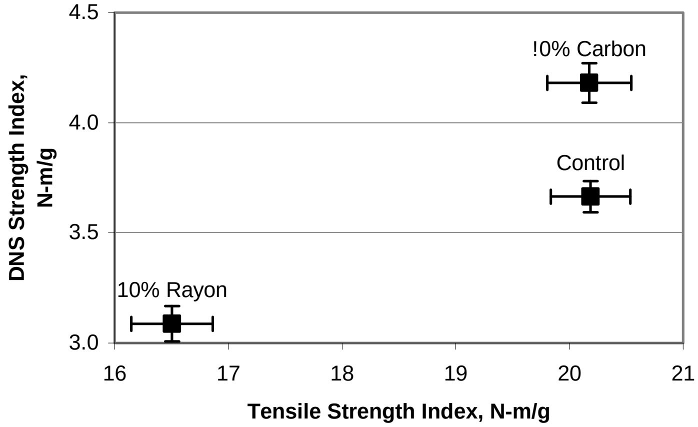


Figure 3. Results of DNS out-of-plane shear testing of eucalyptus handsheets.

In compression and bending stiffness tests, F and E performed comparably. Recall from Table 1 that E had the largest average Scott-bond value. The implied large ply-bond may have helped E to match the performance of F in tests other than DNS.

Perhaps a better comparison is between F and A, because both had comparable Scott-bond values but different ZDFO. Sample F is superior to A in all MD and CD tests; however, the relative performance of A is greatly improved in all the CD tests. This is consistent with the observation of CD-ZDFO in sample A and the absence of CD-ZDFO in sample F. Sample A also improves relative to sample E in most CD tests.

Among CD strength and stiffness tests of samples A, E, and F, the relative improvement of sample A relative to E and F reinforces a possible correlation with ZDFO. Among the differences in the three sheets that could influence the interpretation of results, sheet squareness is probably the most important. An average of MD/CD ratios for the strength and stiffness tests of the sheets gives 1.86 for A, 1.89 for E, and 2.08 for F. The MD ZDFO may make the linerboard F ratio higher, whereas CD ZDFO may decrease the ratio for linerboard A. In that case, the three sheets may have similar underlying squareness, and the present interpretation of results stands.

These uncertainties justify the use of handsheets to study the basic relationship between ZDFO and strength. The dramatic results of Figure 3 need no elaboration. A 10% addition of non-bonding synthetic carbon fibers actually increases shear strength without loss of tensile strength. Handsheet studies also improve the opportunity for direct observation of ZDFO.

A working model for ZDFO creation by carbon fibers emphasizes their length and stiffness. At 3 mm length and too stiff to bend under the hydraulic forces of papermaking, they are unlikely to stratify. Figure 4 is an optical micrograph showing a dark carbon fiber in a cross-section of handsheet. The tilt angle of 7º is consistent with the fiber's length and the handsheet caliper of about 0.4 mm.

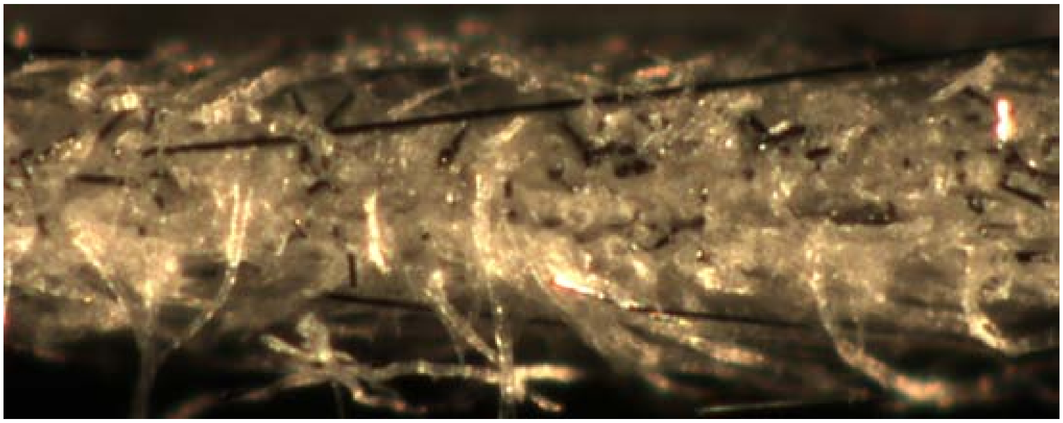


Figure 4. Cross section of a eucalyptus handsheet containing 10% carbon fiber by weight.

Figure 5. Synchrotron x-ray microtomography of a eucalyptus handsheet containing 10% carbon fiber. Dimensions are 700 × 700 × 70 μm^3, from the interior of the sheet.

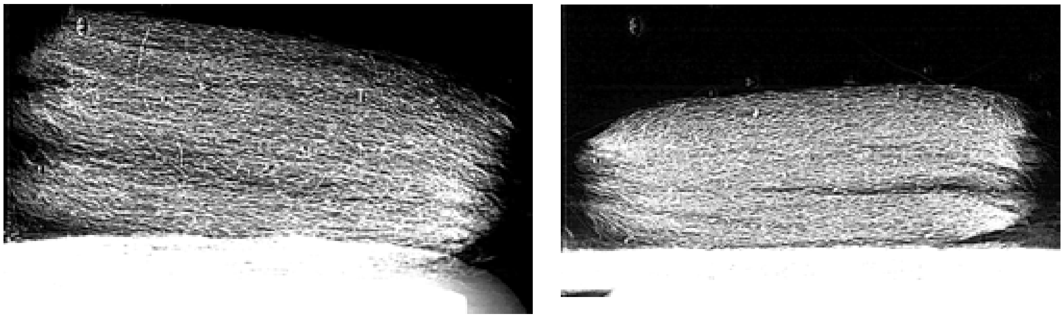
Cellulose fibers encountering this structure are less likely to stratify. Cellulose fibers with z-direction projections ultimately bond with each other and with stratified fibers to give the observed effects. Some evidence of z-oriented fibers is seen in Figure 4, though this could also represent disruption caused in preparing the specimen.

A different view is afforded by synchrotron x-ray microtomography. Figure 5 shows a surface rendering of an interior section of a carbon fiber handsheet. Several straight fiber segments, presumed to be carbon, are seen oriented diagonally within the image. One in the upper right of the image appears to dive into the surface. A circular arc of disruption, not expected in a paper structure, appears to be associated with this event. The scale of the disruption is about 0.35-mm diameter, comparable to the weighted-average eucalyptus fiber length of 0.57 mm.

Figure 6 shows synchrotron x-ray radiographs taken through the cross section of eucalyptus handsheets containing carbon and rayon fibers [15]. The images have been enhanced to improve the visibility of the synthetic fibers. Vertical projections of carbon fibers are common in Figure 6a. Because the fibers are 3 mm long, these are projections of fibers that generally extend into or out of the plane of the image. In Figure 6b, rayon fibers are seen to blend more with the general cellulose structure. In the lots from which the imaged samples were taken, average density of carbon-fiber handsheets was 480 kg/m^3. For sheets with rayon, density was 530 kg/m^3. For control handsheets, density was 560 kg/m^3. Carbon fiber had 2.7 times the effect on density that rayon fiber had, indicating the greater degree of disruption to the cellulose structure.

Summary and Conclusions

Three linerboards with different degrees and orientations of ZDFO were subjected to a battery of conventional tests to determine if the effects of ZDFO on strength and stiffness could be broadly characterized. Linerboard F, with ZDFO limited to fibers generally oriented in the MD, gave the



(a) (b)

Figure 6. X-ray radiographs of eucalyptus handsheets containing 10% carbon fiber (a) or rayon fiber (b). The scale of the images is 1400 µm horizontal by 840 µm vertical.

highest test values 64% of the time, in both MD and CD testing. However, only one test, double-notch-shear strength, was statistically differentiated from results for linerboard E, which had no evidence of ZDFO. Although shear strength is understood to be important for compression strength [3], this expectation was not realized by present tests and requires more study.

A third linerboard, A, was previously found to have CD ZDFO. This linerboard gave the lowest test values from among the three sheets 79% of the time. However, it performed relatively better in CD testing than in MD testing in general, and in double-notch-shear testing in particular. MD double-notch-shear test was the only one where linerboard E, without ZDFO, was statistically inferior to both A and F, with ZDFO.

Comparisons like these tacitly assume the three sheets are equivalent in all ways other than ZDFO. This is not the case. The most likely difference that could be influencing conclusions is sheet anisotropy, especially if F is most MD-oriented and A is least MD-oriented. Resolution of this issue is difficult because the various tests themselves provide a wide range of anisotropies.

Studies with eucalyptus handsheets and synthetic fibers get around the difficulties in comparing commercial papers. The sheets have the same basis weight and are isotropic. A compelling model can be based on the relative stiffness of carbon and rayon fibers. X-ray images show that carbon fibers do not stratify in handsheets, and logic (if not actual images) suggests that cellulose fibers acquire ZDFO as they encounter these stiff structures just before they encounter the fiber mat. Rayon, a form of cellulose, is more like papermaking fibers in stiffness. X-ray images show rayon fibers to be stratified and integrated in the cellulose network.

Rayon produces a loss of bonding sites that translates to a loss of strength. Carbon fiber produces a loss of bonding sites as well. It compensates by producing ZDFO to couple strata together for an increase in shear strength and maintenance of tensile strength.

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